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FINAL REPORT
ON TASK 5

THE THERMAL CONDUCTIVITY OF THERMOCOUPLE GRADE CONSTANTAN ROD

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA
(Contract NAS8-5196)

SOUTHERN RESEARCH INSTITUTE
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Southern Research Institute
Birmingham, Alabama
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SCOPE

The scope of this program was to determine the thermal conductivity of thermocouple grade constantan rod from 500°F (260°C) to the melting point of the material. Duplicate evaluations were made at temperature intervals of 250°F.

The specimen material was obtained from 1 inch diameter rod supplied by NASA in two pieces approximately 8 inches long. Three 1 inch long specimens were machined for the radial inflow apparatus, and two of the same diameter for the comparative rod apparatus.

The thermal conductivity of the constantan rod was determined from 500°F (260°C) to approximately 1100°F (593°C) in the comparative rod apparatus by comparing the temperature drop through the specimen to that in a reference material of known conductivity. From 500°F to 1650°F the conductivity was determined in the radial inflow apparatus which provided a direct measurement technique.

The thermal conductivity of the constantan rod increased almost linearly from 190 Btu/hr/ft^2/°F/in. at 500°F (260°C) to approximately 370 Btu/hr/ft^2/°F/in. at 1700°F (927°C). The evaluations made utilizing both apparatuses were in good agreement.

SPECIMENS

Two pieces of 1 inch diameter constantan rod approximately 8 inches long were supplied by NASA. From one of the rods, two specimens were machined for the comparative rod apparatus, and two specimens with guards were made for the radial inflow apparatus. One additional specimen and guards were machined from the other rod for the evaluations in the radial inflow apparatus. Sketches of the specimen configurations are shown in the attached appendixes for each apparatus.

APPARATUS AND PROCEDURE

Two apparatuses were used to determine the thermal conductivity of constantan rod. One technique involved the determination of the conductivity by comparing the temperature drop through the specimen to the temperature drop through a material with a known thermal conductivity. A description of this apparatus and procedure is attached as Appendix I. Duplicate evaluations were made utilizing this apparatus from 500°F (260°C) to 1000°F (539°C).

Duplicate evaluations were also made from 500°F to 1650°F (899°C) in the radial inflow apparatus. This apparatus provided a direct measurement technique as described in Appendix II. Copper granules were used in the annulus between the specimen and the calorimeter tube, and chromel-alumel thermocouples were used to measure the temperature drop through the gauge section of the specimen.

To confirm the melting point of the constantan, a 0.025 inch diameter constantan wire was weighted and suspended in the furnace and heated slowly until it melted. The temperature of the wire and the heater tube were monitored with an optical pyrometer and indicated that the wire melted when it reached a temperature of 2173°F (1189°C) and the heater tube was at a temperature of 2218°F (1214°C). These temperatures were used as the limiting conditions during the evaluations to ensure that the specimen was not melted.

DATA AND RESULTS

The results of the evaluations made in the comparative rod apparatus are shown in Table 1. The conductivity of the second specimen was less than that of the first at about 1000°F by approximately 15 Btu/hr/ft^2/°F/in. or 5%. The evaluations on both of these specimens were made using Armco iron for the reference material; however, several points were checked with stainless steel references, and the results were within the precision limits of the equipment.

The results of the evaluations in the radial inflow apparatus contained somewhat more scatter than that from the comparative rod apparatus, as shown in Table 2. The values obtained in this apparatus at below 1000°F were for comparison only and not used in the final analysis.

The combined results of the evaluations made in the two apparatuses are shown in Figure 1. Observe that the values obtained from the two different apparatuses agreed quite well at the common temperature of 1000°F.

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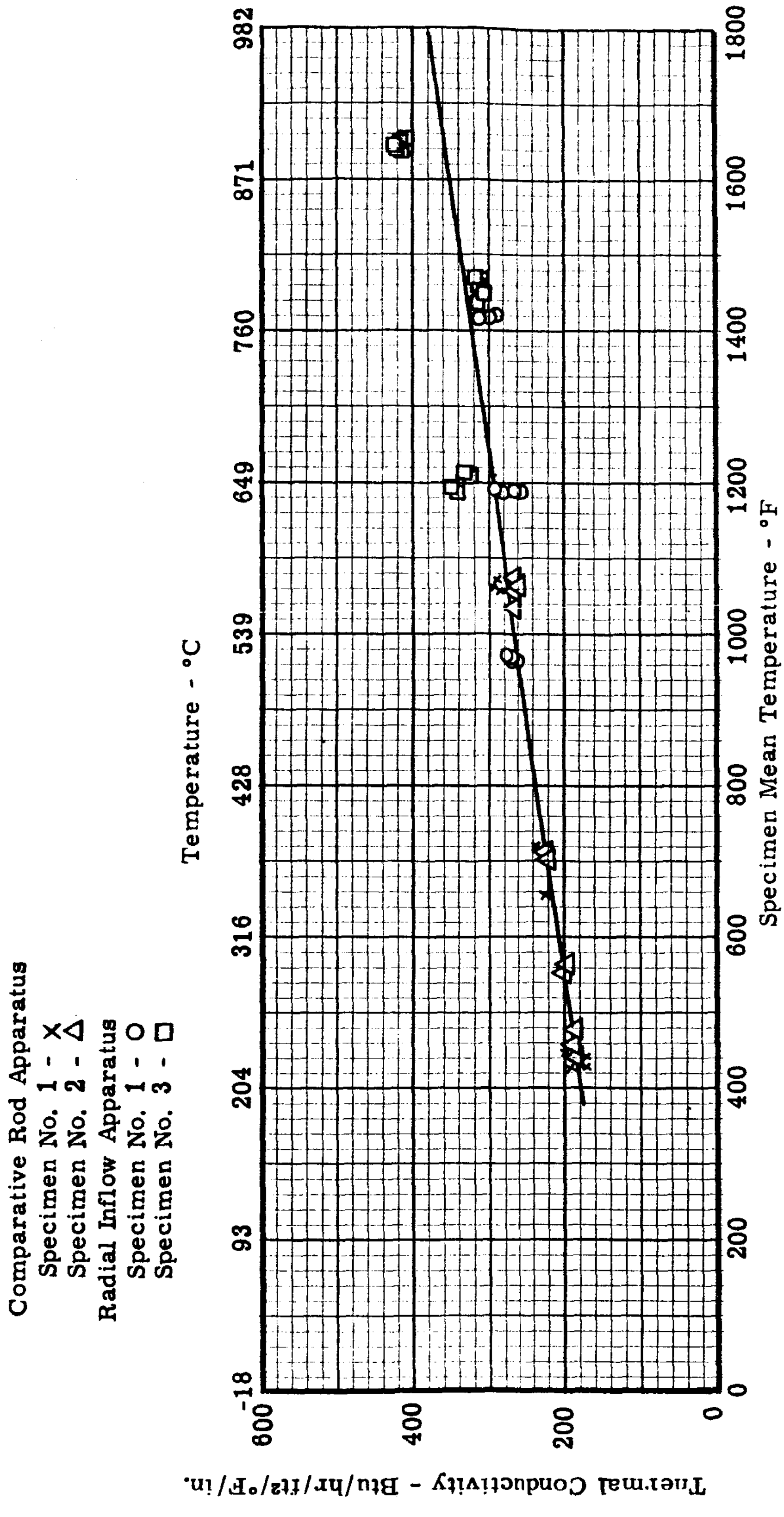

Figure 1. Combined Results of Thermal Conductivity Evaluations on Thermocouple Grade Constantan Rod

Table 1.

Thermal Conductivity of Thermocouple Grade Constantan Rod Determined in the Comparative Rod Apparatus with Armco Iron References

SRI Run Number	Conductivity of Reference-K_1 (Btu/hr/ft^2/°F/in.)	Δt through Reference Δt_1 (°F)	Conductivity of Reference-K_2 (Btu/hr/ft^2/°F/in.)	Δt through Reference-Δt_2 (°F)	Δt through Specimen Δt_s (°F)	Conductivity of Specimen-K_s (Btu/hr/ft^2/°F/in.)	Specimen Mean Temperature (°F)
Specimen #1	423	15.1	402	21.2	38.6	193	425
	411	15.5	400	19.2	38.1	184	432
	411	15.0	400	19.4	38.2	182	436
	419	15.5	398	19.0	37.5	187	444
	390	32.0	341	44.0	62.2	221	651
	364	33.5	332	43.9	58.5	229	714
	298	70.9	256	87.4	74.7	291	1070
	298	68.6	256	84.2	73.0	288	1058
	299	69.0	259	83.5	73.2	289	1053
Specimen #2	395	25.0	365	24.3	46.8	200	560
	415	17.7	389	15.3	34.4	193	478
	420	15.8	398	14.4	32.8	188	438
	416	17.2	393	15.4	34.6	191	457
	396	23.6	370	22.3	43.6	202	551
	366	34.9	334	36.7	55.7	224	700
	364	35.2	333	38.6	55.7	230	707
	286	69.7	255	80.9	76.9	264	1063
	294	72.5	254	82.0	77.2	272	1071
	298	70.9	258	79.9	77.0	271	1052
	302	68.5	262	78.5	77.2	268	1032

Table 2.

The Thermal Conductivity of 1 inch Diameter Thermocouple Grade Constantan Rod as Determined in the Radial Inflow Apparatus

SRI Run Number	Time	Specimen Outer Face Temperature °F	ΔT Across $\frac{3}{16}$" Specimen Gage Length °F	Total Heat Removed by $\frac{1}{2}$" Calorimeter Gage Length Btu/hr	Mean Temperature of Specimen °F	Specimen Thermal Conductivity Btu/hr/ft²/°F/in.
Specimen # 1	12:43	-	30	218.4	789	221.5
	12:44	-	30	218.5	787	221.6
	12:47	-	27	205.8	789	208.7
	12:50	-	27	206.8	787	209.7
	1:56	-	32	333.5	965	278.6
	1:59	-	33	332.9	963	278.0
	2:03	-	34	316.1	964	264.0
	2:05	-	35	312.5	964	261.0
	3:05	-	46	447.2	1189	288.6
	3:07	-	46	433.8	1185	280.0
	3:11	-	42	409.1	1186	264.1
	3:12	-	43	401.4	1185	259.1
	4:17	-	54	597.3	1417	314.1
	4:20	-	54	572.9	1418	301.3
	4:22	1710	53	560.3	1420	294.7
	Off 4:30					Both thermocouples burned out during reversing.
Specimen # 3	4:47	-	20	129.2	659	193.1
	4:50	-	19	128.9	684	192.7
	4:56	-	18	122.7	682	183.4
	5:00	-	18	119.7	680	178.9
	6:07	-	37	263.4	941	213.8
	6:12	-	36	254.8	940	206.8
	6:16	-	35	252.5	933	204.8
	6:18	1498	34	247.8	930	201.1
	7:46	1697	44	447.7	1186	353.2
	7:48	1706	42	439.5	1184	346.7
	7:54	1712	32	424.0	1208	334.5
	7:59	1722	29	422.5	1207	333.3
	9:54	1900	45	543.4	1469	319.5
	9:57	1900	49	538.8	1467	316.8
	9:59	1905	47	540.5	1464	317.8
	10:10	1880	55	535.4	1434	314.8
	10:12	1870	43	531.3	1442	312.4
	11:00	2105	45	750.7	1656	411.6
	11:03	2100	42	756.2	1652	414.6
	11:09	2135	69	775.1	1637	425.0
	11:12	2130	58	759.8	1637	416.5
	11:14	2140	56	757.7	1648	415.4
	11:17	2130	65	777.7	1643	426.4
	Off 11:19					

APPENDIX

APPENDIX I

A COMPARATIVE ROD APPARATUS FOR MEASURING THERMAL CONDUCTIVITY TO 1500°F

Southern Research Institute's comparative rod apparatus is used to measure thermal conductivities of a wide variety of materials from -300°F to 1500°F. This apparatus, shown schematically in Figure 1, consists basically of two cylindrical reference pieces of known thermal conductivity stacked in series with the cylindrical specimen. Heat is introduced to one end of the rod, composed of the references and specimen, by a small electrical heater. A cold sink or heater is employed at the opposite end of the rod as required to maintain the temperature drop through the specimen at the preferred level. Cylinders of zirconia may be inserted in the rod assembly to assist in controlling the temperature drop. Radial losses are minimized by means of radial guard heaters surrounding the rod and consisting of three separate coils of 26-gage Kanthal wire wound on a 2 inch diameter alumina core. The annulus between the rod and the guard heaters is filled with diatomaceous earth. Surrounding the guard is an annulus of diatomaceous earth enclosed in an aluminum shell.

The specimens and references (see Figure 2) are 1 inch diameter by 1 inch long. Thermocouples located $\frac{3}{4}$ inch apart in radially drilled holes measure the axial temperature gradients. Thermocouples located at matching points in each guard heater are used to monitor guard temperatures, which are adjusted to match those at corresponding locations in the test section.

In operation, the apparatus is turned on and allowed to reach steady state. The guard and rod heaters are adjusted to minimize radial temperature gradients between the rod and guard sections consistent with maintaining equivalent functions of K_r times ΔT in the references. Temperatures are measured on a Leeds and Northrup Type K-3 potentiometer, and the temperature gradients calculated. A typical temperature profile in the test section is shown in Figure 3.

The thermal conductivity of the specimen is calculated from the relation

$$K_s = \frac{K_1 \Delta T_1 + K_2 \Delta T_2}{2 \qquad \Delta T_S} \; \frac{\Delta X_S}{\Delta X_r}$$

where K_1 and K_2 are the thermal conductivities of the upper and lower references; ΔT_1, ΔT_2, and ΔT_S are the temperature gradients in the upper and lower references and specimen, respectively; ΔX_S and ΔX_r are the distances between thermocouples in the specimen and references.

Note that for purely axial heat flow, the products $K_1 \Delta T_1$ and $K_2 \Delta T_2$ should be equal. Due to imperfectly matched guarding and other factors, this condition is seldom attained in practice; therefore, the average of the two values is used in the calculations. Their difference is maintained as small as possible, usually within 5% of the smaller.

For identical specimens, the ratio $\Delta X_s / \Delta X_r$ should be unity but may vary due to the uncertainty in hole locations. To prevent introducing an additional error in calculations, ΔX is determined as follows: The depth of the hole is measured by inserting a snugly fitting drill rod in the hole, measuring the projecting length and subtracting it from the total length of the rod. The slope, or angle the hole makes with the perpendicular to the specimen axis, is determined by making measurements to the face of the hole and the outer end of the drill rod with respect to a datum plane, using a dial gage. From these measurements, the location of the bottom of the hole can be calculated.

For reference materials, Armco iron or copper are used with high conductivity specimens, 316 stainless steel with specimens of intermediate conductivities, and teflon, Pyroceram 9606, or pyrex with low conductivity specimens. Extensive calibration of the apparatus, using these reference materials as standards, has yielded accuracies to about 5% error, when sufficient care is exercised to maintain closely matched temperatures between the guard and test sections. Even with careless matching, the error is only about 10 % so the system is not particularly sensitive to minor unbalances.

To establish the accuracy of the apparatus some initial runs were made on 316 stainless steel, using Armco iron as the reference. The data, shown in Figure 4, are somewhat higher than those reported by Lucks and Deem[1], but agree well with values reported by several steel manufacturers. Note that the data scatter is less than 5%. The data on stainless steel were confirmed by evaluating Armco iron, using 316 stainless steel as reference. These data are shown in Figure 5 in comparison with values reported by Powell[2], who compiled his curve from the data of numerous investigators, and estimated its accuracy to be within $\pm$ 2% over the range from 0° to 1000°C. The comparative rod data for Armco iron, which were computed using the solid curve of Figure 4 for the thermal conductivity of the stainless steel reference, agree with Powell's data within 5%, thus confirming the data obtained for stainless steel.

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[1]WADC TR 58-476, "The Thermophysical Properties of Solid Materials," Armour Research Foundation, November 1960

[2]Powell, R. W., Proc. 3rd Conf. on Thermal Conductivity, 322-341 (1963)

Some additional data obtained on the comparative rod apparatus are shown in Figure 6. Figure 6 shows the thermal conductivity data for ATJ graphite, with grain, using Armco Iron as the reference material. These data show excellent agreement with earlier data obtained here and by other sources[3-5]. The maximum scatter of the comparative rod points was about 5%.

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[3] ASD-TDR-62-765, "The Thermal Properties of Twenty-Six Solid Materials to 5000°F or Their Destruction Temperatures," Southern Research Institute, August, 1962

[4] Pears, C. D., Proc. 3rd Conf. on Thermal Conductivity, 453-479 (1963)

[5] Fieldhouse, et al, WADC TR 55-495, Part 3 (1955)

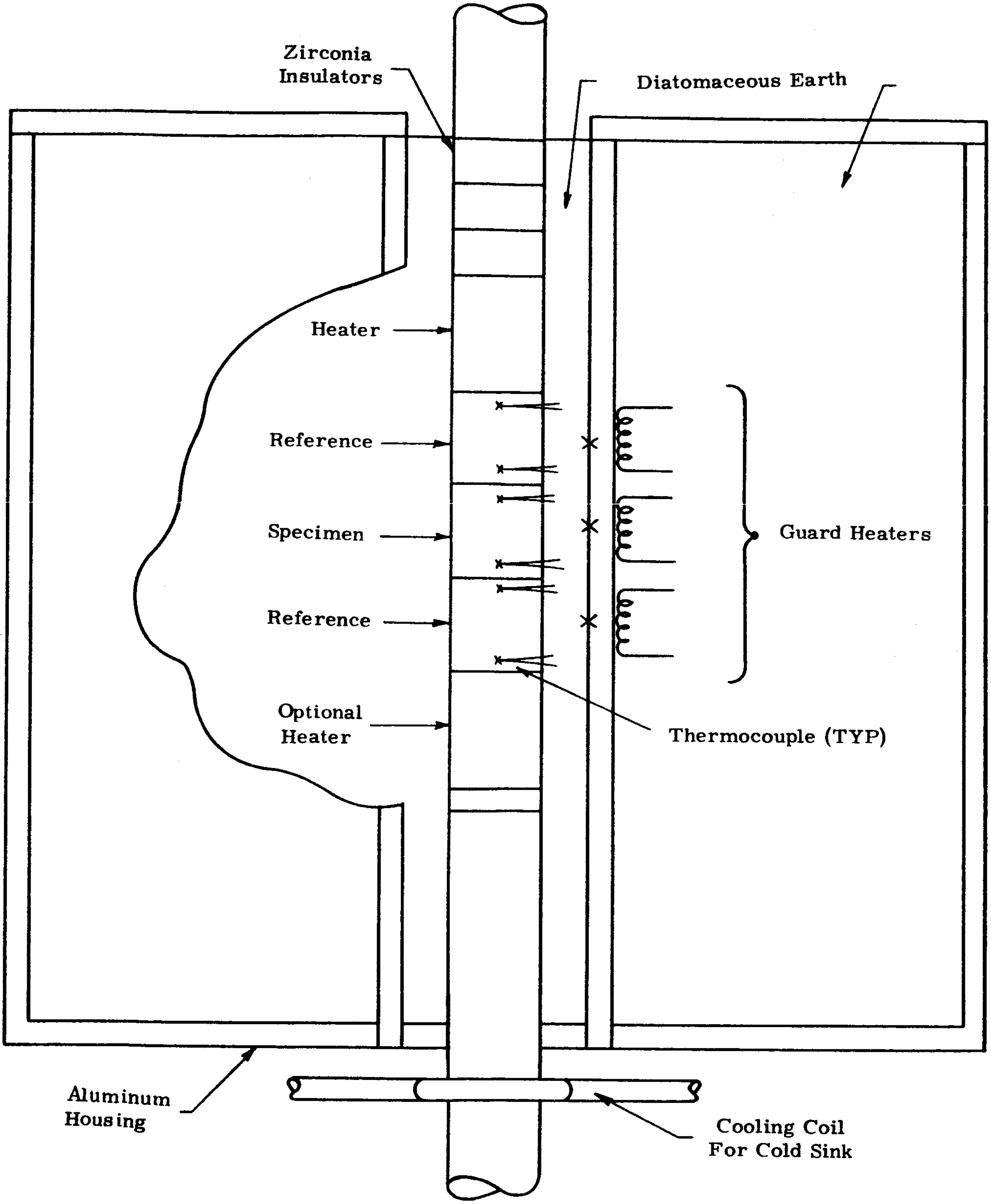
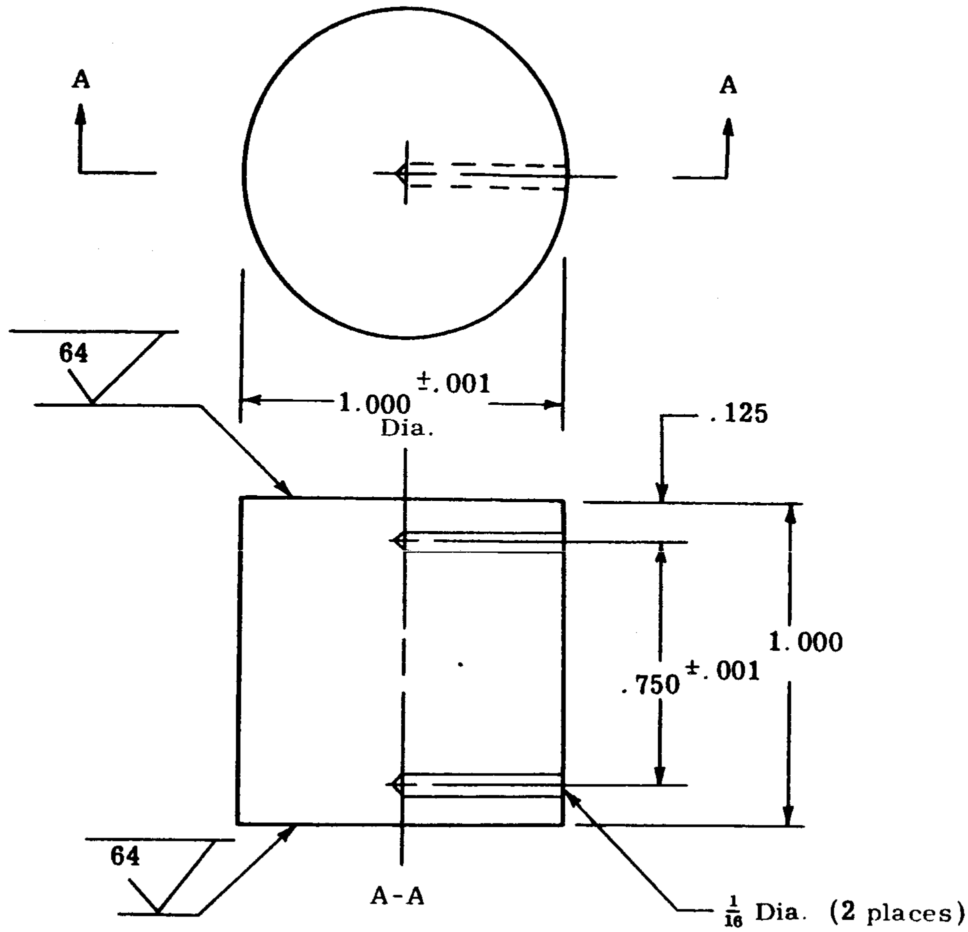


Figure 1. Schematic of Comparative Rod Thermal Conductivity Apparatus



Notes: 1. Tolerances ± .003 unless otherwise noted.
2. Upper and lower surfaces to be flat and ⊥ specimen ℄ within .001 TIR.

Figure 2. Specimen Configuration for Comparative Rod Thermal Conductivity Apparatus.

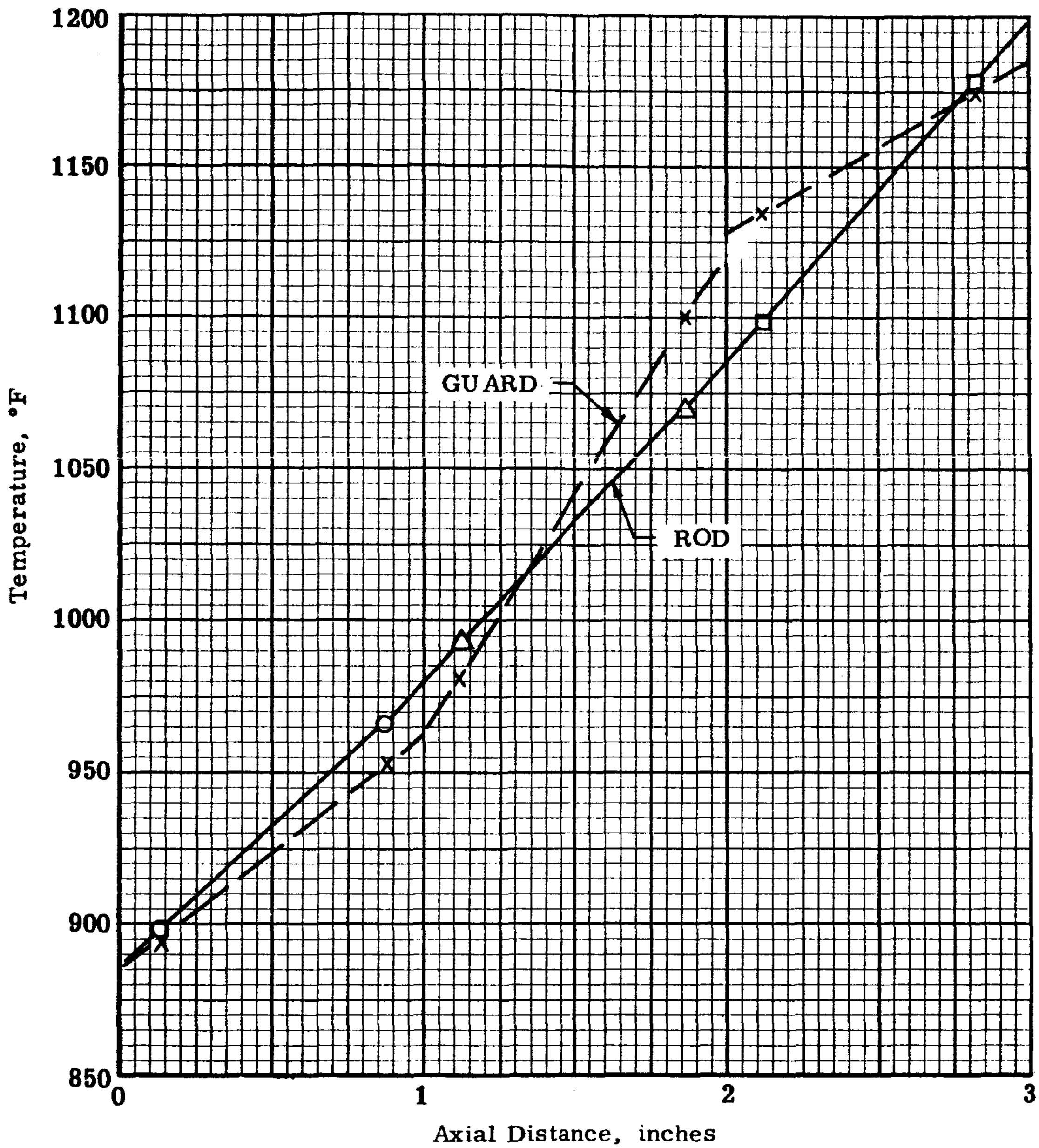


Figure 3. Typical Temperature Profile in Test Section.

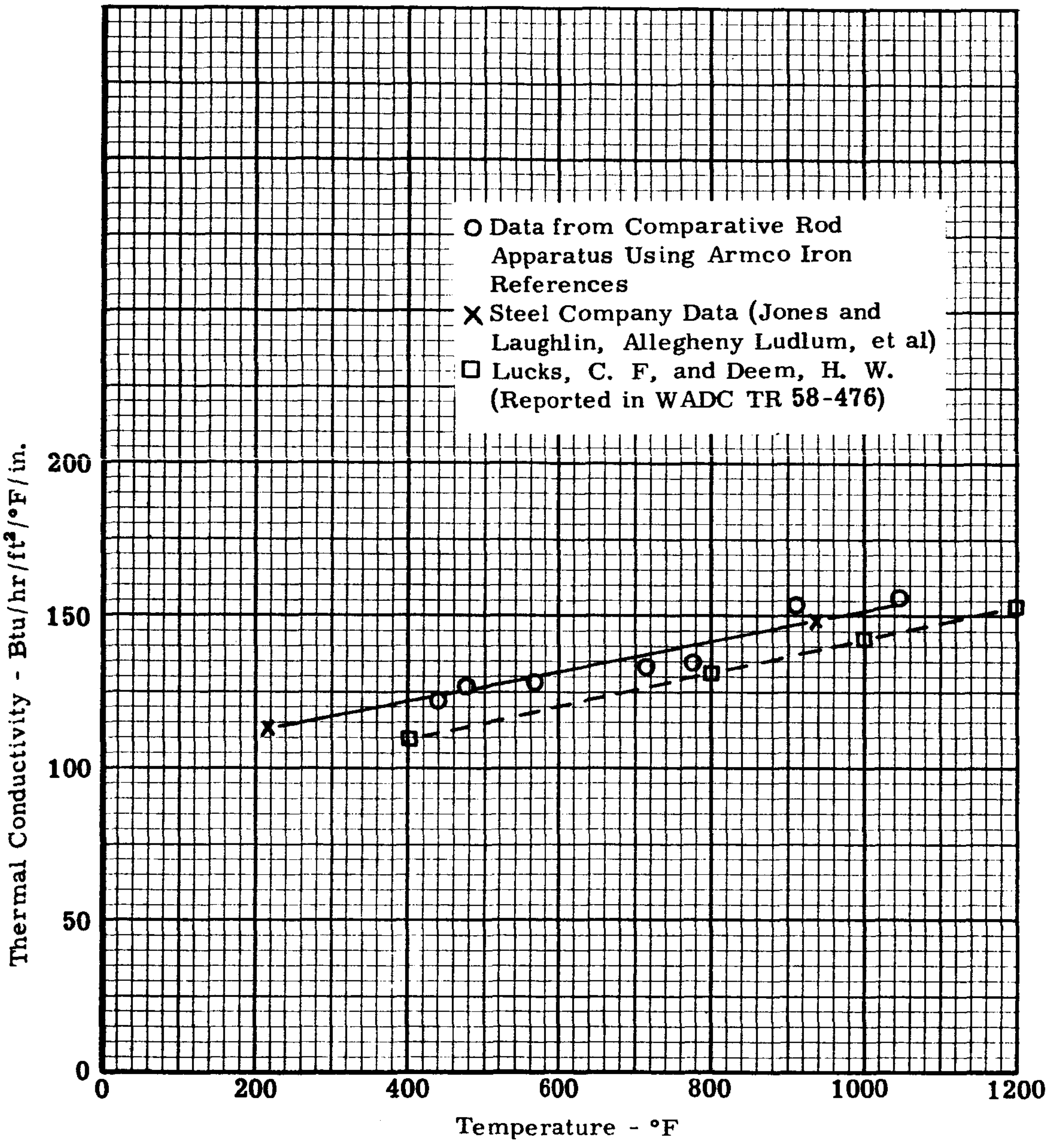


Figure 4. The Thermal Conductivity of Type 316 Stainless Steel.

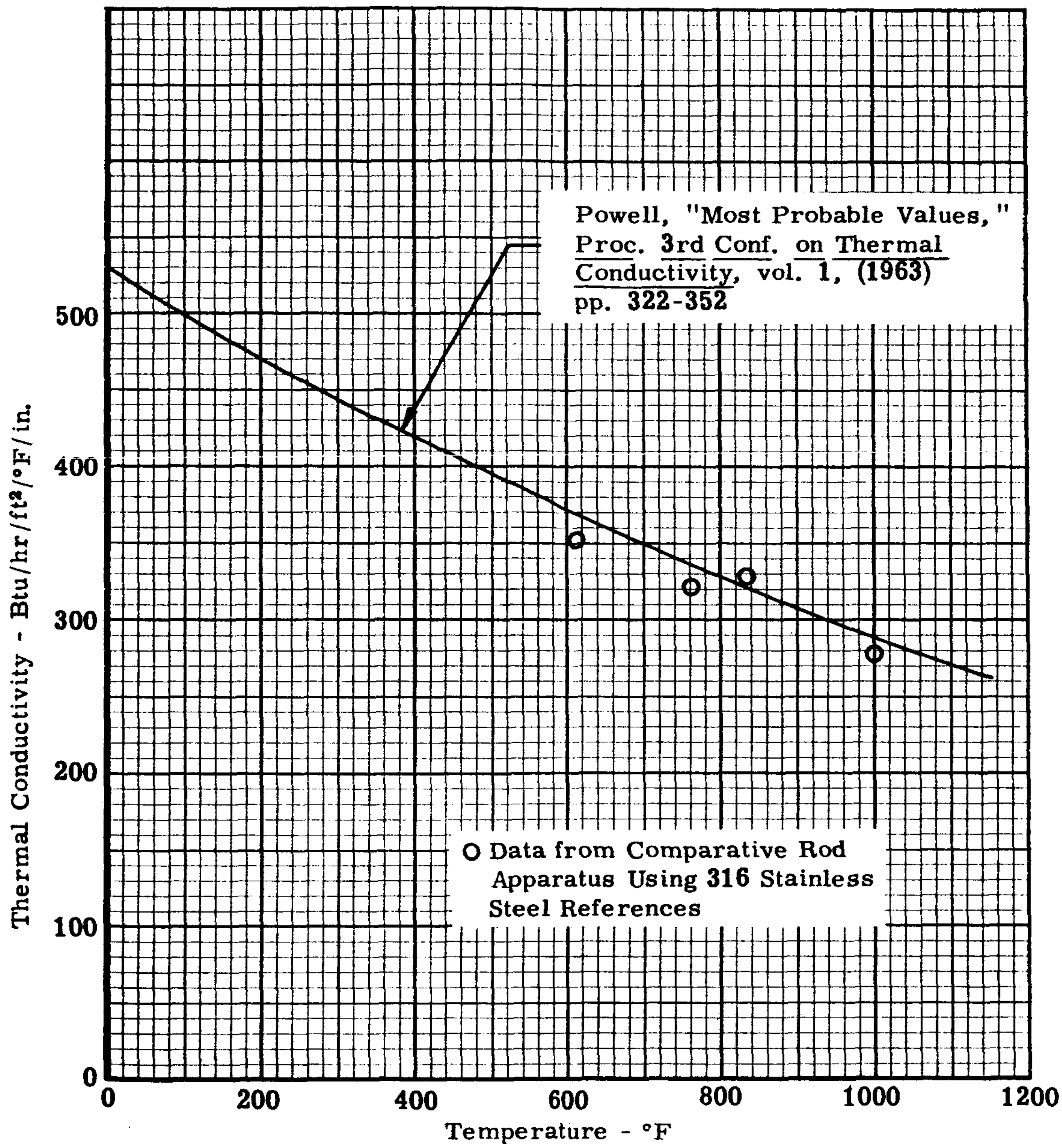


Figure 5. The Thermal Conductivity of Armco Iron.

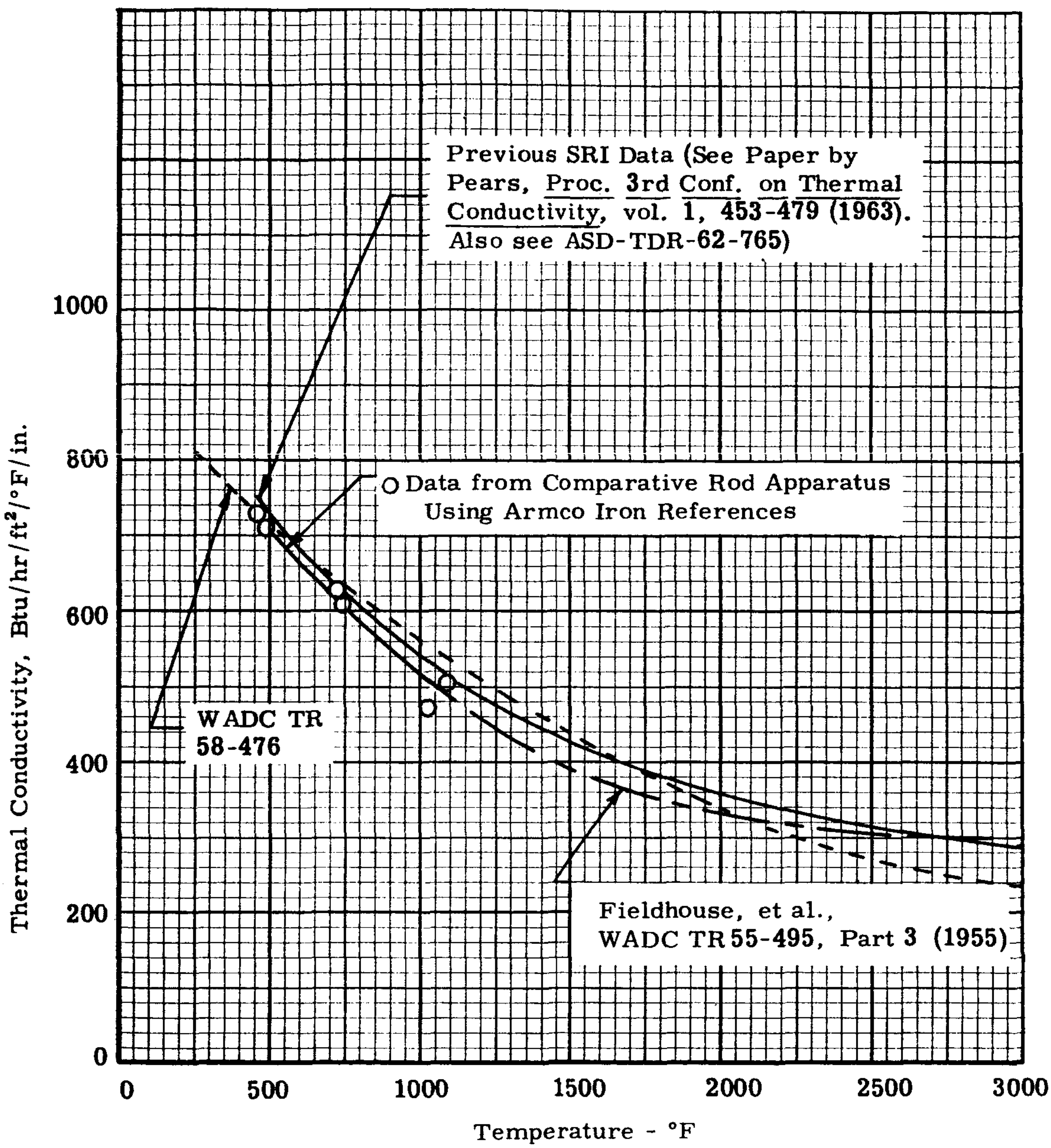


Figure 6. Thermal Conductivity of ATJ Graphite, With Grain.

APPENDIX II

THERMAL CONDUCTIVITY TO 5000°F

The thermal conductivity is determined with a radial heat flow apparatus that utilizes a specimen 1" long. The equipment allows a direct measurement of the thermal conductivity rather than a measurement relative to some standard reference material. A picture of the apparatus ready to be installed in the furnace is shown in Figure 1. The furnace and associated equipment for the thermal conductivity work is shown in Figure 2. In addition to the specimen, the apparatus consists primarily of (1) a water calorimeter that passes axially through the center of the specimen, (2) guards made from the same specimen material at both ends of the specimen to reduce axial heat losses, (3) sight tubes that allow the temperature at selected points in the specimen to be determined either by thermocouples or optical pyrometer, and (4) an external heat source (see Figure 3). The water calorimeter provides a heat sink at the center of the specimen to create a substantial heat flow through the specimen and allows the absolute value of the heat flow to be determined. Thermocouples mounted $\frac{1}{2}$" apart in the calorimeter water stream measure the temperature rise of the water as it passes through the gage portion of the specimen. By metering the water flow through the calorimeter, it is possible to calculate the total radial heat flow through the $\frac{1}{2}$" gage section of the specimen from the standard relationship $Q = WC\Delta T$. W is the weight of water flowing per hour, C is the specific heat of water, and ΔT is the temperature rise of the water as it passes through the gage section.

The standard specimen configuration is 1" long, 1" outside diameter, $\frac{1}{4}$" inside diameter, with $\frac{5}{64}$" holes, $\frac{1}{2}$" deep, on radii of $\frac{7}{32}$" and $\frac{13}{32}$". The $\frac{5}{64}$" holes in the specimen permit temperature measurement at selected points within the specimen.

A $\frac{1}{2}$" long upper guard and a $\frac{1}{2}$" long lower guard of specimen material are placed above and below the 1" specimen to maintain a constant radial temperature gradient throughout the entire specimen length and therby prevent axial heat flow in the specimen. The outer ends of the specimen guards are insulated with graphite tubes filled with thermatomic carbon. These tubes also hold the specimen in alignment. The combined effect of specimen guards and thermatomic carbon insulation permits a minimum axial temperature gradient within the specimen. This gradient is not detectable by optical pyrometer readings. Visual inspection of the specimens after runs have verified that no large axial temperature gradient exists in the specimen. The guards, made of specimen material, display axial distortion of the isothermal lines for approximately $\frac{1}{4}$" from the outer ends before reaching an apparent constant axial temperature.

The annulus between the specimen inside diameter and the $\frac{7}{32}$" outside diameter of the calorimeter tube is packed with either copper granules, graphite or zirconia powder. This annulus packing provides a positive method for centering the calorimeter within the specimen and promote good heat transfer between specimen and calorimeter.

On low temperature runs (up to 2000°F), the specimen temperature is measured with Chromel-Alumel thermocouples inserted into the specimen through the sight tubes. At high temperatures, the temperatures are read by optical pyrometer sighting down the sight tube through a right-angle mirror device.

In Figures 1 and 3 showing a typical conductivity calorimeter apparatus ready for insertion into a furnace for a run, a water-cooled copper section can be seen at the top of the unit. This section provides permanent sight tubes to within about $2\frac{1}{2}$" of the guard specimen, in addition to a permanent mount for the right-angle mirror device used with the optical pyrometer. Within the short zone between the water-cooled section and the top guard, thin-walled graphite sight tubes are fitted. The remainder of the annulus is filled with thermatomic carbon insulation.

During thermal conductivity runs, the following data are recorded: (1) power input, (2) specimen face temperature, (3) specimen temperatures in the gage section at the $\frac{7}{32}$" and $\frac{13}{32}$" radii, (4) temperature of the calorimeter water at two points $\frac{1}{2}$" apart axially within the specimen center, and (5) water flow rate through the calorimeter. At least 3 readings are made at each general temperature range to determine the normal data scatter and to minimize the error that might be encountered in a single reading.

All thermocouple readings are measured on a Leeds and Northrup K-2 null balance potentiometer used in conjunction with a galvanometer of 0.43 microvolts per mm deflection sensitivity. All optically measured temperatures are read with a Leeds and Northrup Type 8622 optical pyrometer. The flow rate of the calorimeter water is measured with a Fischer and Porter Stabl-Vis Flowrator.

The thermal conductivity values are computed from the relation

$$K = \frac{QL}{\Delta T \bar{A}}$$

where Q is the heat flow to the calorimeter within the specimen gage section, $\bar{A}$ is the log mean area for the specimen gage length, ΔT is the specimen temperature change across the specimen gage length, and L is the gage length over which the specimen ΔT is measured.

The heat flow Q is determined by the calorimeter. $\bar{A}$ and L are calculated directly for the particular specimen configuration. ΔT is determined directly from the observed temperature difference across the specimen gage length.

Extensive calibration work on materials of known thermal conductivity has indicated a percision of of 7% over the entire temperature range. See ASD TDR 62-765 for an error analysis.

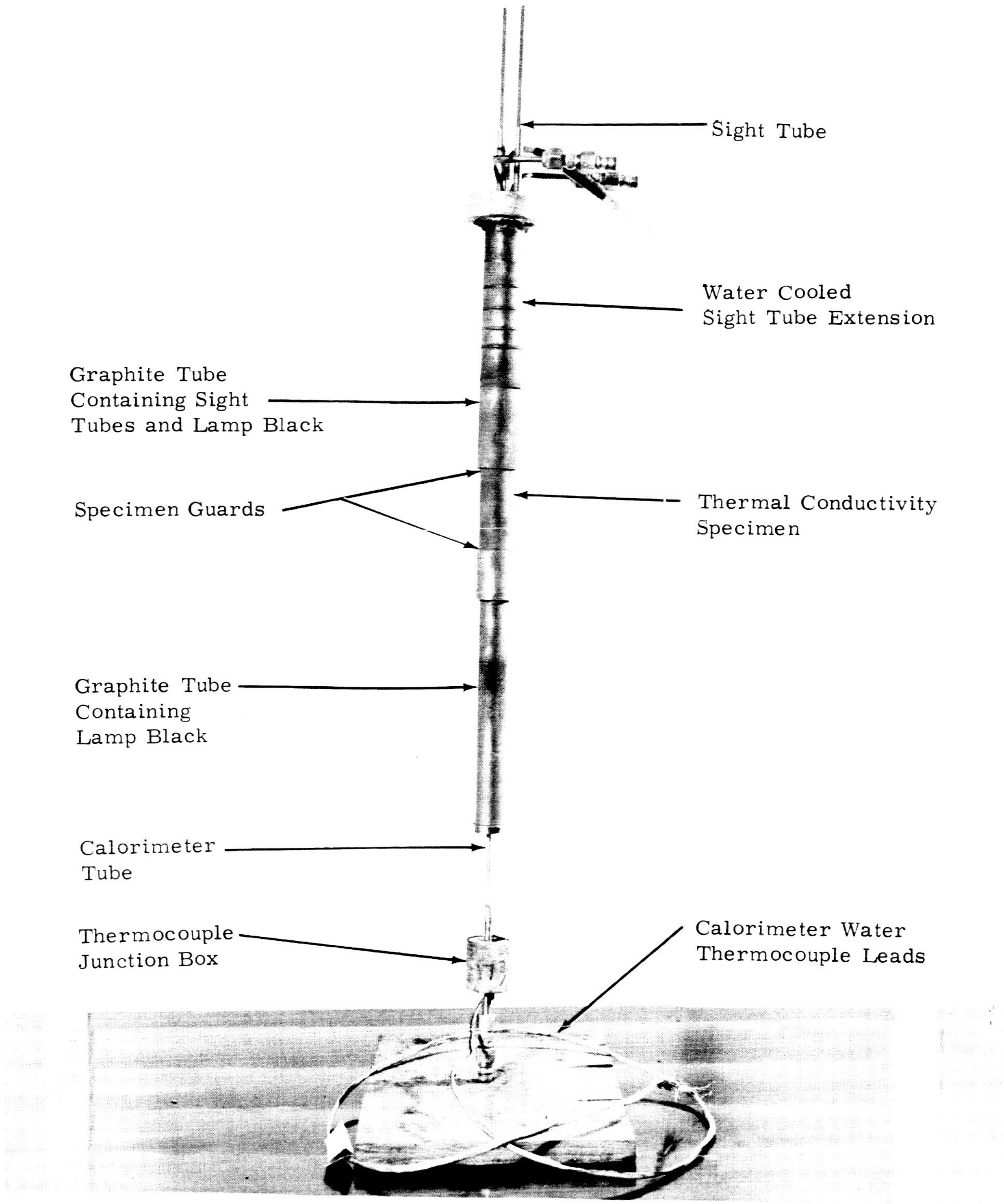


Figure 1. Picture of the Radial Thermal Conductivity Apparatus

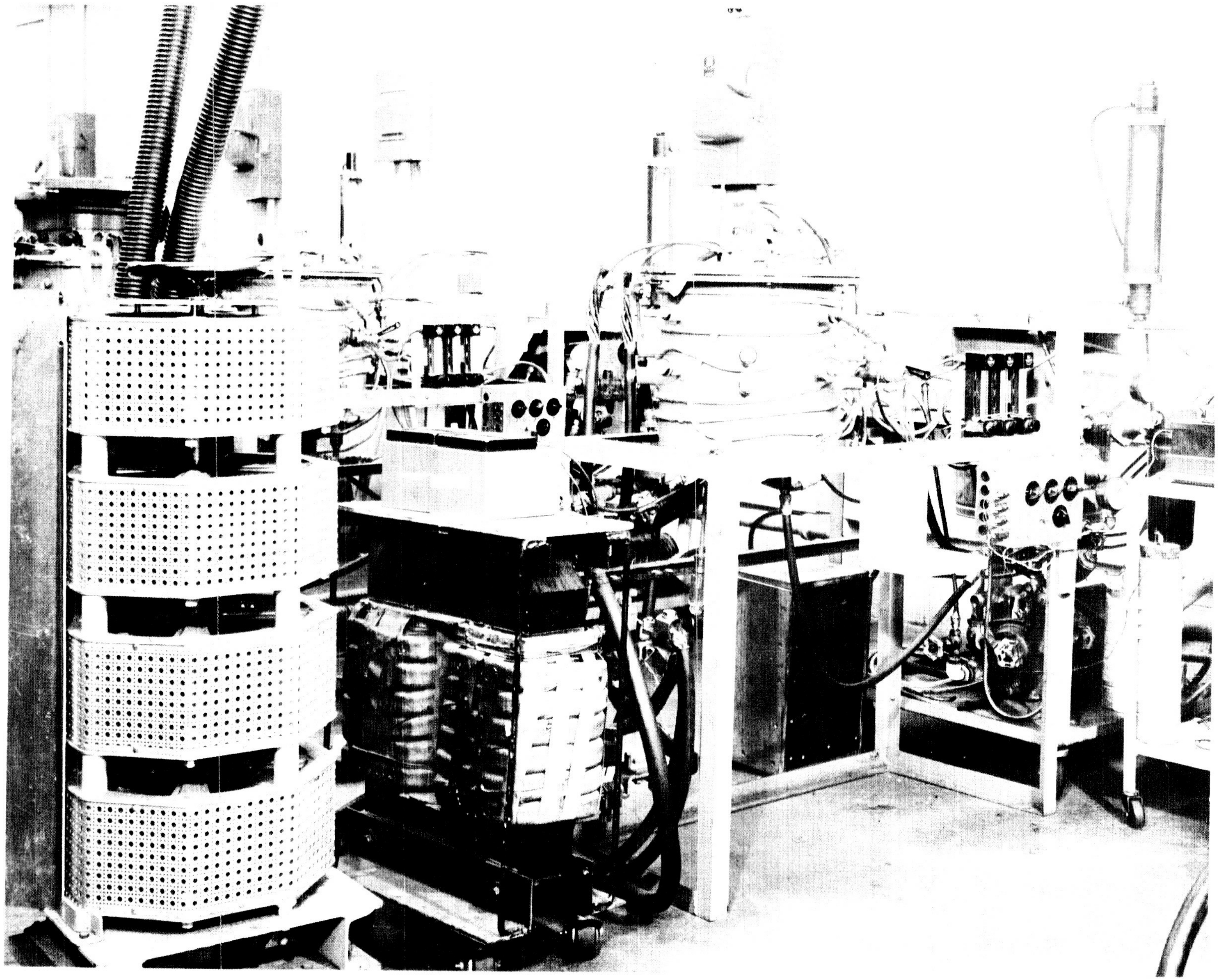


Figure 2. Furnace with Thermal Conductivity Apparatus Installed

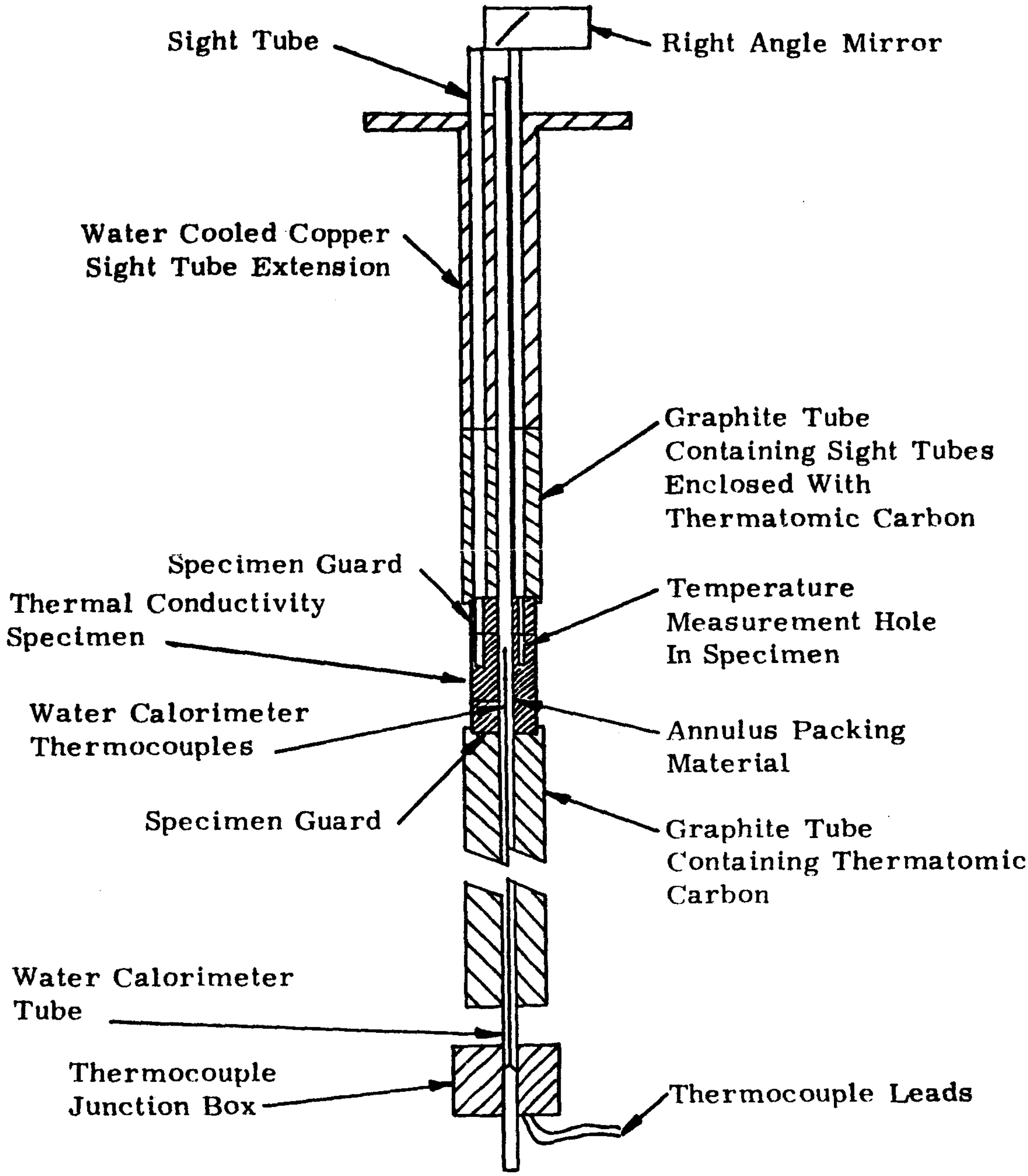


Figure 3. Cross-section Schematic of the Thermal Conductivity Apparatus.